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6. AUTHOR(S)
Dr. Kookrin Char

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Conductus, Inc.
969 West Maude Avenue
Sunnyvale, CA 94086

8. PERFORMING ORGANIZATION
AFOSR-TR-96
0320

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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In summary, we have developed Co-doped barrier SNS junctions and succeeded in incorporating the junctions on ground planes. The integrity of the ground planes was confimed by electrical testing of the isolation as well as by the decrease of the SQUID inductance on the ground planes. However, actual demonstration of SFQ circuits was not achieved due to larger variation of the critical current and the reduced I_cR_n value when the critical current was lower.

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Final Technical Report

for SBIR-93 Phase II

HTS S-N-S Technology for Digital Logic (F49620-93-C-0058)

1. List of Research Objectives

The fundamental goals of this two year program are:

1. To refine the SNS junction process developed under Phase I for use in SFQ digital circuits,
2. To design, fabricate and test a family of digital logic gates using the S-N-S process, and
3. To demonstrate a complex digital circuit whose complexity will depend upon the progress in process development.

2. Achievement of the Research Effort

During Phase I, several barriers for SNS Josephson junctions including $(CaSr)RuO_3$, Co-doped YBCO, and Ca-doped YBCO were investigated. In order to achieve the necessary uniformity of the junction parameter, a key issue of interface resistance was identified. The interface resistance between YBCO and $(CaSr)RuO_3$ was found to be highly inhomogeneous, causing a huge variation in the critical current and the resistance. However, in the case of doped YBCO, presumably due to excellent match in lattice constants and thermal expansion coefficients, the interface resistance was measured to be smaller than 10^{-10} Ωcm^2.

For Phase II, Ca-doped YBCO and Co-doped YBCO barriers have been further developed for use in SFQ circuits. SNS junctions based on Ca-doped YBCO have been fabricated and their chracteristics analyzed. Underdoped Co-doped YBCO barriers have been the most extensively studied, specifically as a function of doping, thickness and temperature. The data have been analyzed in terms of conventional proximity effect and systematic changes with the doping level have been observed, including a crossover from the clean limit to the dirty limit and decay lengths consistent with microscopic material parameters. However, a percolative process due to inhomogeneous doping could not be ruled out.

By focusing on the processing aspects of the junction fabrication such as surface morphology, edge formation, and barrier deposition, we have been working towards improving the uniformity of the junctions, particularly with respect to the critical current. The test chip used for this purpose is shown in Fig. 1.

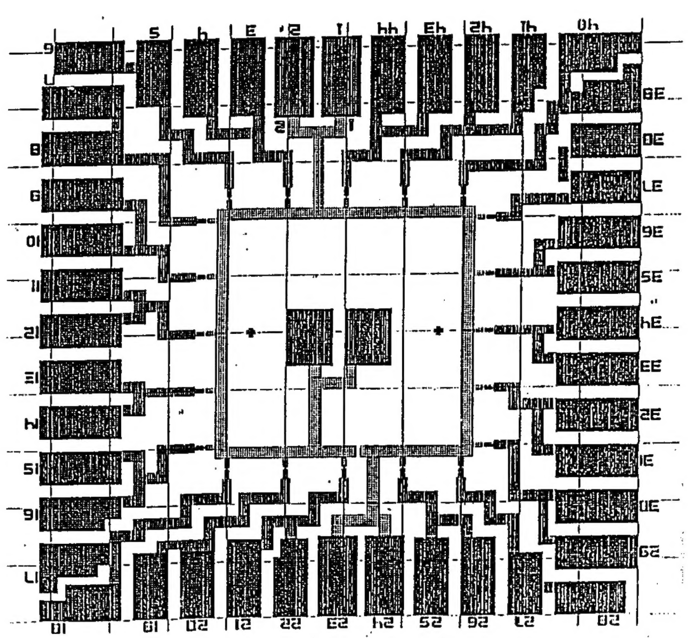

Fig. 1. Omnidirectional test chip layout

We have demonstrated a critical current uniformity $\sigma \sim 15$ to 20 %, as shown in Fig. 2. The uniformity was attained using 5 % Co-doped barriers with the average critical current value around 1 to 2 mA and the average resistance value around 0.1 to 0.2 Ω.

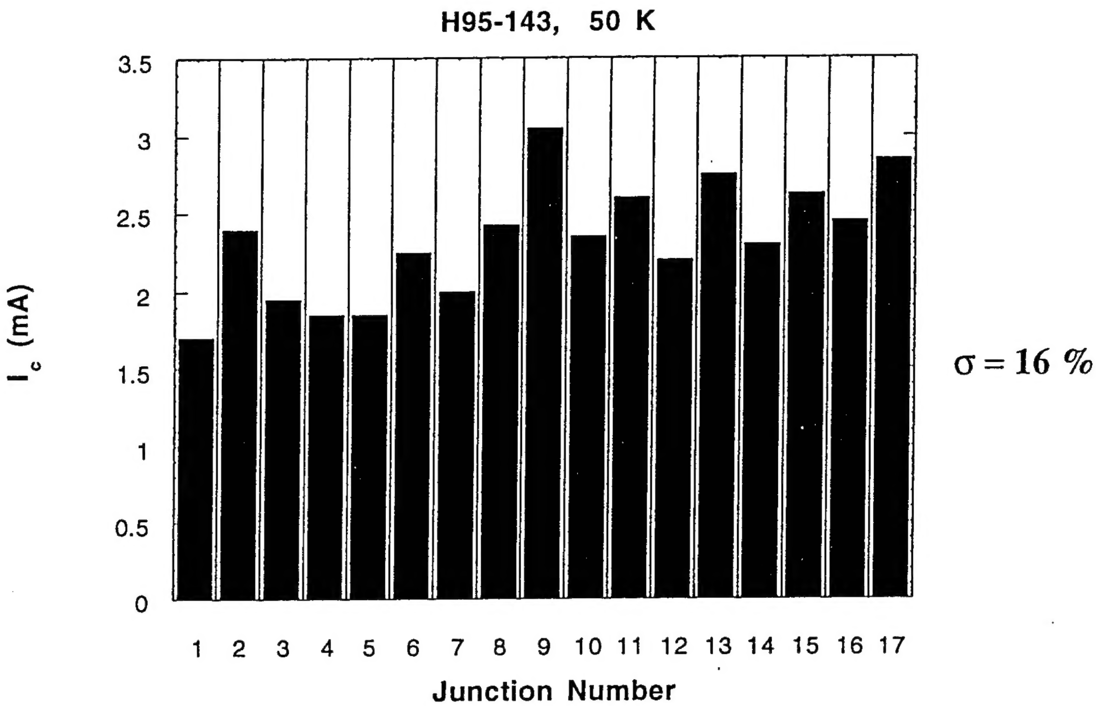

Fig. 2. Junction uniformity off ground plane.

SFQ circuits are based on superconducting loops containing a Josephson junction that move single flux quanta from one loop to another. The inductance of the loop, L, and the critical current of the junction, I_c, should satisfy the relation $I_c L < \Phi_0 = 2 \times 10^{-7}$ gauss-cm^2. Given the typical I_c values between 500 μA and 1 mA, the inductance of a loop should be smaller than 4 pH. This is the reason why our initial SFQ logic gate design based on co-planar lines was not successful. The inductance of such a co-planar line was found to be larger than 3 pH per square, producing at least 12 pH for a loop. The only way to reduce the inductance further

is to incorporate a ground plane in a microstrip geometry, requiring further development of the SNS junction process on top of a ground plane.

After development of atomically smooth YBCO ground planes, the insulation between the ground plane and the junction electrode layers was found to be adequate. The proper function of the ground plane was confirmed by measuring the inductance of a SQUID on and off the ground plane, as shown in Fig. 3.

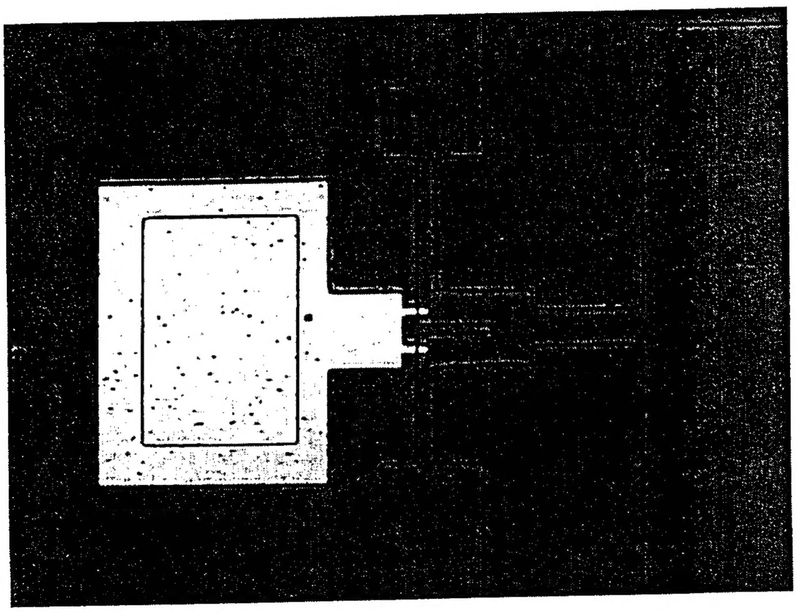

Fig. 3. SQUID on ground plane with via.

The inductance per square was found to be about 1 pH around 60 K from the relation $\Phi_0 = L \times \Delta I_{inj}$, shown in Fig. 4. Incorporation of the SNS junction process on top of the ground plane was accomplished. The junction uniformity $\sigma \sim 15$ to 20% has been obtained on top of ground planes, as shown in Fig. 5.

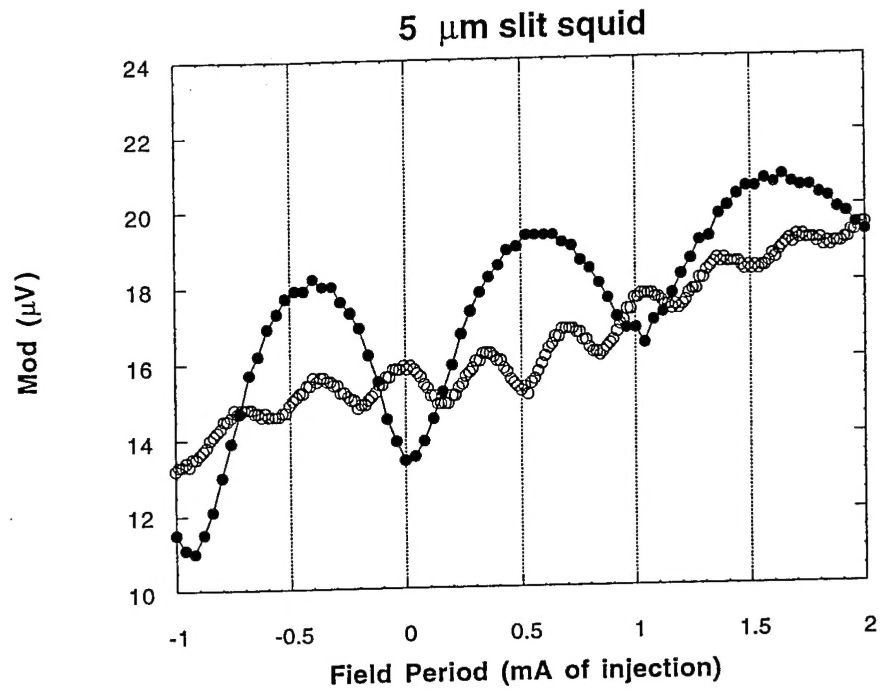

Fig. 4. SQUID modulation on and off ground plane at 70 K.

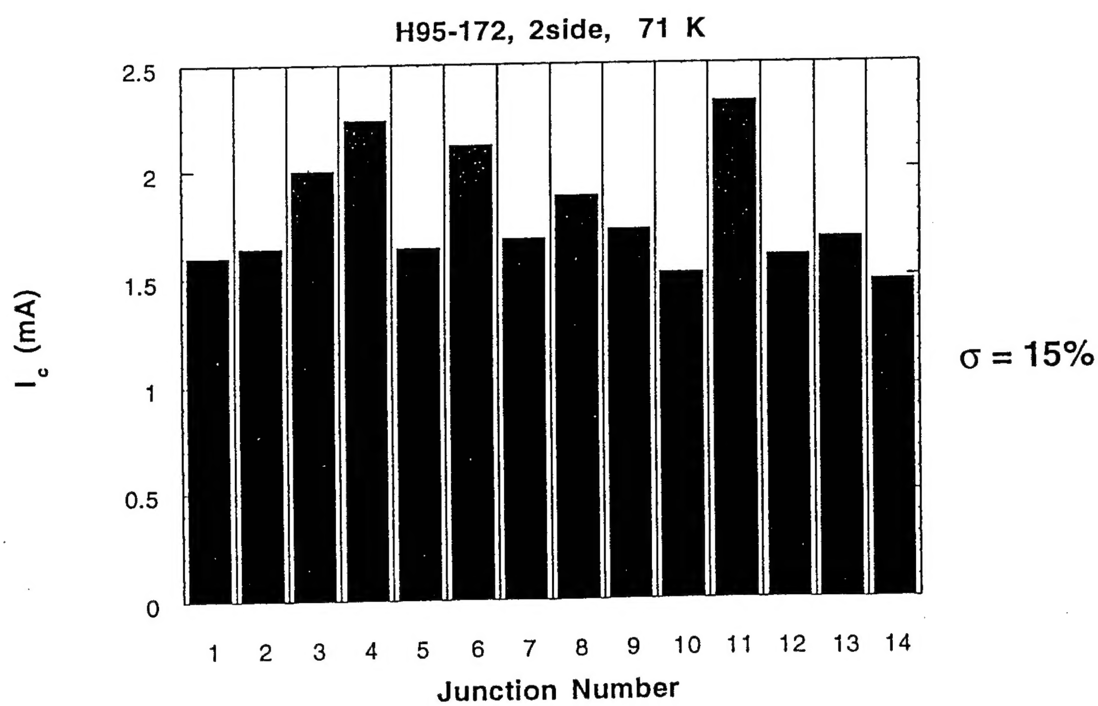

Fig. 5. Junction uniformity on ground plane.

The remaining problem we have not completely solved is to attain good uniformity in the I_c value around 300 μA. This reduction of I_c is necessary since the inductance of a loop will be at least 4 to 5 pH even with a ground plane. In the case of SNS junctions, the reduction of I_c can be achieved by increasing the thickness of the barrier, which at the same time reduces the I_cR_n product. In the temperature range where the I_c is about 300 μA, the uniformity was found not as good as in the lower temperature range of I_c about 1 mA. Better uniformity with I_c values around 300 μA on top of ground planes will be required in order to have functioning SFQ circuits. In addition, higher R_n values will be necessary for higher speed operation as well as ease of interface circuits with conventional readout electronics.

In summary, we have developed Co-doped barrier SNS junctions and succeeded in incorporating the junctions on ground planes. The integrity of the ground planes was confimed by electrical testing of the isolation as well as by the decrease of the SQUID inductance on the ground planes. However, actual demonstration of SFQ circuits was not achieved due to larger variation of the critical current and the reduced I_cR_n value when the critical current was lower.

3. List of Written Publications

[1] "Study of interface resistances in epitaxial $YBa_2Cu_3O_{7-x}$/barrier/$YBa_2Cu_3O_{7-x}$ junctions", K. Char, L. Antognazza, and T. H. Geballe, Appl. Phys. Lett. **63**, 2420 (1993).

[2] "Noise characteristics of $YBa_2Cu_3O_{7-x}/CaRuO_3/YBa_2Cu_3O_{7-x}$ Josephson junctions", K. E. Myers, K. Char, M. S. Colclough, and T. H. Geballe, Appl. Phys. Lett. **64**, 788 (1994).

[3] "Origin of nonuniform properties of $YBa_2Cu_3O_{7-x}/CaRuO_3/YBa_2Cu_3O_{7-x}$ Josephson edge junctions", E. Olsson and K. Char, Appl. Phys. Lett. **64**, 1292 (1994).
[4] "Properties of $YBa_2Cu_3O_{7-x}/YBa_2Cu_{2.79}Co_{0.21}O_{7-x}/YBa_2Cu_3O_{7-x}$ edge junctions", K. Char, L. Antognazza, and T. H. Geballe, Appl. Phys. Lett. **65**, 904 (1994).
[5] "Interface and proximity effects in SNS Josephson junctions based on YBCO with epitaxial barriers", K. Char, L. Antognazza, and T. H. Geballe, Physica C **235-240**, 3351 (1994).
[6] "Proximity effect in $YBa_2Cu_3O_{7-\delta}/YBa_2(Cu_{1-x}Co_x)_3O_{7-\delta}/YBa_2Cu_3O_{7-\delta}$ junctions: from the clean limit to the dirty limit with pair breaking", L. Antognazza, S. J. Berkowitz, T. H. Geballe, and K. Char, Phys. Rev. B **51**, 8560 (1995).
[7] "Properties of high-T_c Josephson junctions with $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ barrier layers", L. Antognazza, B. H. Moeckly, T. H. Geballe, and K. Char, Phys. Rev. B **52**, 4559 (1995).

4. List of Professional Personnel

Kookrin Char

Louis Antognazza

5. Interactions

[1] "Properties of interfaces in YBCO epitaxial SNS junctions", K. Char, presented at 4th International Superconductive Electronics Conference, August 11-14, 1993, Boulder, Colorado, USA.

[2] "Epitaxial SNS Josephson junctions based on YBCO", K. Char and L. Antognazza, presented at International Workshop on High Temperature Superconduting Electron Devices, May 26-28, 1994, Shistler, British Columbia, CANADA.

[3] "The importance of interface in epitaxial SNS edge junctions", K. Char, L. Antognazza, and T. H. Geballe, presented at Applied Superconductivity Conference, October 16-21, 1994, Boston, Massachusetts, USA.

[4] "YBCO proximity effect Josephson junctions in dirty and clean limits", K. Char, American Physical Society March meeting, San Jose, March 19-24, 1995.

[5] "Interfaces and SNS edge junctions of YBCO", K. Char, 5th International Superconductive Electronics Conference, Nagoya JAPAN, September 18-21, 1995.

[6] "Material issues in YBCO SNS junctions: interfaces and barriers", K. Char, Material Research Society Meeting, Boston, November 27- December 1, 1995.

6. New Inventions

We have filed a patent application (08/345,318) on the use of Ca-doped and Co-doped YBCO as the barrier material in SNS junctions. A copy of the patent application was attached with the annual report last year.